

Charm Production at RHIC to $O(\alpha_s^3)$

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Abstract

We present results on rapidity and transverse momentum distributions of inclusive charm quark production in heavy-ion collisions at RHIC, including the next-to-leading order, $O(\alpha_s^3)$, radiative corrections and the nuclear shadowing effect. We find the effective, nuclear K-factor to be $K(y) \approx 1.4$ for $|y| \leq 3$ in the rapidity distribution, while $1 \leq K(p_T) \leq 3$ for $1\text{GeV} \leq p_T \leq 6\text{GeV}$ in the p_T distribution. We incorporate multiple parton scatterings in our calculation of the fraction of all central events that contain at least one charm quark pair. We obtain the effective A -dependence of the charm cross sections. Finally, we comment on the possibility of detecting the quark-gluon plasma signal as an enhanced charm production in heavy-ion collisions at RHIC.

The main goal of the future heavy-ion colliders, such as RHIC, is to study the properties of nuclear matter under extreme conditions, and in particular to search for the formation of a new state of matter, the quark-gluon plasma [1]. With the assumption that high energy nuclear collisions lead to the thermalized system, RHIC energies are sufficiently large to produce very dense matter, of the order of several GeV/fm^3 , well above the critical density necessary to create the quark-gluon plasma [2]. The problem of finding a clean, detectable signal for this phase is currently one of the most challenging theoretical problems. In the last few years, the possible signals, such as thermal photons, dileptons and J/Ψ suppression, have been investigated in detail and found to have yields comparable in magnitude with those expected from a simple extrapolation of hadronic collisions [3]. Recently, open charm production in heavy-ion collisions has been proposed as an elegant method for probing the possible formation of the quark-gluon plasma [4]. However, in order to determine whether the enhanced charm production at RHIC can be unambiguously interpreted as a signal of QGP, one needs to have control of the other sources of charm production. The standard competing process is charm production through the hard collisions of partons inside the nuclei. In addition to being relevant as a background for the signal of quark-gluon plasma, this type of charm production is useful tool for studying the perturbative aspects of strong interactions and for determining the nuclear screening/shadowing effect on the gluon distribution in a nucleus.

In this letter we present results of calculations of the rapidity and transverse momentum distributions of inclusive charm quark production in Au-Au collisions at RHIC, including the $O(\alpha_s^3)$ radiative corrections and the nuclear shadowing effect. We determine the size of the gluon contribution to the charm production at RHIC. We also calculate the fraction of central and inelastic events at RHIC that will contain charm quarks which satisfy unitarity constraints by properly taking into account multiple nucleon scatterings. In our calculations we use the latest set of two-loop evolved parton densities in a nucleon obtained from global fits of data from deep inelastic lepton-nucleon collisions [5]. We take the nuclear shadowing effect in the quark distribution from the recent measurements in deep inelastic lepton-nucleus collisions [6]. We assume that the amount of shadowing present in the gluon distribution is the same as in the quark. To illustrate the importance of next-to-leading order contributions and the nuclear shadowing effects, we determine the *effective* (i.e. nuclear) K-factor defined as the ratio of the particular distribution

to the leading-order distribution without any nuclear effects. We show that this K-factor is very different than the one in hadronic collisions, and that in general, it can not be approximated by a constant. We also determine the effective A-dependence of the charm cross sections. Finally, we comment on our results for the number of charm quarks produced in central rapidity region in central Au-Au collisions in the context of quark-gluon plasma signatures at RHIC.

In perturbative QCD, the inclusive cross section for charm production in nuclear collisions is obtained by convolution of parton densities in nuclei with a hard scattering parton cross section [7]. In our calculation, for the parton cross sections, we include leading-order subprocesses, $O(\alpha_s^2)$, such as $q + \bar{q} \rightarrow Q + \bar{Q}$ and $g + g \rightarrow Q + \bar{Q}$, and next-to-leading order contributions, $O(\alpha_s^3)$, such as $q + \bar{q} \rightarrow Q + \bar{Q} + g$, $g + q \rightarrow Q + \bar{Q} + g$, $g + \bar{q} \rightarrow Q + \bar{Q} + g$ and $g + g \rightarrow Q + \bar{Q} + g$. The double differential inclusive distribution of charm production in central AA collisions can be written as

$$\frac{dN_c}{d^2p_T dy} = T_{AA}(0) \frac{d\sigma_c}{d^2p_T dy}, \quad (1)$$

where the double differential inclusive cross section is given by

$$\frac{d\sigma_c}{d^2p_T dy} = \sum_{i,j}^{partons} \int dx_a dx_b F_i^A(x_a, Q^2) F_j^A(x_b, Q^2) \frac{d\hat{\sigma}_{i,j}(Q^2, m_c, \hat{s})}{d^2p_T dy}, \quad (2)$$

and $T_{AA}(0)$ is the nuclear overlapping density at zero impact parameter, $F_i^A(x, Q^2)$ is the parton structure function in a nucleus, x_a and x_b are the fractional momenta of the incoming partons, \hat{s} is the parton-parton c.m. energy ($\hat{s} = x_a x_b s$). The parton differential cross section calculated to $O(\alpha_s^3)$ can be written as [8]

$$\frac{d\hat{\sigma}_{i,j}}{d^2p_T dy} = \frac{\alpha_s^2}{\hat{s}} h_{i,j}^{(0)} + \frac{\alpha_s^3}{2\pi \hat{s}^2} h_{i,j}^{(1)}. \quad (3)$$

Expressions for the functions $h_{i,j}^{(0)}$ and $h_{i,j}^{(1)}$ can be found in Ref. 8. The coupling constant $\alpha_s(Q^2)$ that appears in Eq. (3) is given by

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2N_f) \ln \frac{Q^2}{\Lambda^2}} \left[1 - \frac{6(153 - 19N_f) \ln \ln Q^2 / \Lambda^2}{(33 - 2N_f)^2 \ln Q^2 / \Lambda^2} \right], \quad (4)$$

where Q^2 is the renormalization scale, Λ is the QCD scale parameter and N_f is the number of flavors. We take the factorization scale in the structure functions to be $2m_c$ and we consider the renormalization scales $Q = m_c$ and $Q = 2m_c$. We do not evolve the structure functions below $Q = 2m_c$, because for $Q^2 \leq 8.5 \text{ GeV}^2$ their behavior is not very well known [9]. For the mass of the charm quark we use $m_c = 1.5 \text{ GeV}$.

The double differential distribution for inclusive charm quark production in *inelastic* Au-Au collisions can be obtained from Eq. (1) by replacing $T_{AA}(0)$ with $A^2/\sigma_{inelastic}^{AA}$, where $\sigma_{inelastic}^{AA} \approx 4\pi R_A^2$.

To obtain the number of nucleon-nucleon collisions per unit of transverse area at fixed impact parameter, we consider the nuclear overlapping function [10]

$$T_{AA}(b) = \int d^2b_1 T_A(|\vec{b}_1|) T_A(|\vec{b} - \vec{b}_1|), \quad (5)$$

where the nuclear profile function, $T_A(b)$, is the nuclear density integrated over the longitudinal size, i.e.

$$T_A(b) = \int_{-\infty}^{\infty} dz \rho_A(\sqrt{b^2 + z^2}) \quad (6)$$

For nuclear density we use the Woods-Saxon distribution [11] given by

$$\rho(r) = \frac{n_0}{[1 + e^{(r-R_A)/d}]}. \quad (7)$$

The density and the nuclear overlapping function are normalized so that $\int d^3r \rho(r) = A$ and $\int d^2b T_{AA}(b) = A^2$. For central collisions the overlapping function can be approximated by $T_{AA}(0) = A^2/\pi R_A^2$, which gives $T_{Au-Au}(0) = 30.7 \text{ mb}^{-1}$.

The nuclear parton distribution, if nucleons were independent, would be given as A times the parton structure function in a nucleon. However, at high energies, the parton densities become so large that the sea quarks and gluons overlap spatially and the nucleus can not be viewed as a collection of uncorrelated nucleons. This happens when the longitudinal size of the parton, in the infinite momentum frame of the nucleus, becomes larger than the size of the nucleon. Partons from different nucleons start to interact and through annihilation effectively reduce the parton density in a nucleus. When partons inside the nucleus completely overlap, they reach a saturation point. Motivated by this simple parton picture of the nuclear shadowing

effect and taking into account the $A^{1/3}$ dependence obtained by considering the modified, nonlinear modifying factor to the Altarelli-Parisi equations with gluon recombination included, the parton structure function in a nucleus can be written as [12]

$$R(x, A) \equiv \frac{F_i^A(x, Q^2)}{AF_i^N(x, Q^2)} = \begin{cases} 1 - \frac{3}{16}x + \frac{3}{80} & .2 < x \leq 1 \\ 1 & x_n < x \leq .2 \\ 1 - D(A^{1/3} - 1) \frac{1/x - 1/x_n}{1/x_A - 1/x_n} & x_A \leq x \leq x_n \\ 1 - D(A^{1/3} - 1) & 0 < x < x_A \end{cases} \quad (8)$$

where F_i^N is the parton structure function in a nucleon, $x_n = 1/(2r_p m_p)$, x_A is a saturation point ($x_A = 1/(2R_A m_p)$), m_p is the mass of the proton, r_p is the radius of a proton and R_A is the radius of the nucleus. The only free parameter is a constant D which can be determined by fitting the data.

Comparison of the shadowing function with all deep inelastic lepton-nucleus data on the ratio $F_2^A(x, Q^2)/F_2^D(x, Q^2)$ [6] indicate that Eq. (8) has much steeper x -dependence, especially for $0.002 \leq x \leq 0.1$, the region of relevance to charm production at RHIC and LHC energies. In addition, the onset of saturation for the ratio of structure functions for Xe to Deuterium is observed at values of x about order of magnitude smaller than those predicted by the parton recombination model [6]. Thus, it is not surprising that even the best fit of Eq. (8) to the data overestimates the observed shadowing effect by about 15%. Consequently charm production calculated with this shadowing function would be underestimated by about 40%.

In our calculation we use the shadowing function that has recently been proposed as the best fit of EMC, NMC and E665 data [11] and is given by [13]

$$R(x, A) = \begin{cases} \alpha_3 - \alpha_4 x & x_0 < x \leq 0.6 \\ (\alpha_3 - \alpha_4 x_0) \frac{1+k_q \alpha_2 (1/x - 1/x_0)}{1+k_q A^{\alpha_1} (1/x - 1/x_0)} & x \leq x_0 \end{cases} \quad (9)$$

The values for the parameters k_q , α_1 , α_2 , α_3 , α_4 and x_0 can be found in Ref. 13. It is interesting to note that for $x \sim x_0 = 0.14$, this shadowing function has a form similar to the shadowing function motivated by the parton recombination picture. The main difference is the onset of saturation, which occurs at smaller value of x than x_A of Eq. (8) and much more gradually. In addition, the A -dependence is much weaker, namely $A^{0.1}$.

By integrating Eq. (2) and multiplying by $T_{AA}(0)$ (for central collisions) or by A^2/σ_{in}^{AA} (for inelastic collisions), we obtain rapidity distribution, trans-

verse momentum distribution and the total cross section for the inclusive charm quark production in AA collisions. We compare our results for the total charm cross section with the low-energy hadronic and nuclear data [14], for the energy range $20\text{GeV} \leq \sqrt{s} \leq 55\text{GeV}$. We find very good agreement with all the data for the choice of scale $Q = m_c$. When $Q = 2m_c$ is used, our cross sections are slightly smaller than the measured values. Detailed comparison of our results with low-energy measurements of differential distributions and the total cross section for charm production will be published separately in Ref. 15.

Here we present our results on rapidity and transverse momentum distributions for the inclusive charm production in Au-Au collisions at RHIC. In our calculation we use the two-loop evolved parton structure functions, MRS-S0 [5] with $\Lambda_5 = 140\text{MeV}$. By using two other sets of structure functions, MRS-D0 and MRS-D- [5], we find that theoretical uncertainty due to the choice of the nucleon structure function is only 10%. This is not surprising because the average x -value probed with charm production at $\sqrt{s} = 200\text{GeV}$ is about 10^{-2} , which is still within the range of x for which there is deep inelastic lepton-nucleon scattering data. Another theoretical uncertainty is the choice of the renormalization scale. We find about 40% lower cross sections when we use the scale $Q = 2m_c$ instead of $Q = m_c$. Since the low-energy data seem to be better described with the choice of scale $Q = m_c$, we will present most of our results with that particular choice. Our results for differential distributions ($d\sigma/dy$, $d\sigma/dp_T$, $d\sigma/dx_F$ and $d\sigma/dp_T dy|_{y=0}$) and for the total charm cross section in heavy-ion collisions at LHC, (including the theoretical uncertainties), will be included in Ref. 15.

Our result for the rapidity distribution of inclusive charm production in central Au-Au collisions at RHIC is presented in Fig. 1a (solid line). We also show the rapidity distribution when nuclear shadowing is not included (dotted line) and the leading-order results with shadowing (short-dashed line) and without shadowing (long-dashed line). We note the the *shape* of the rapidity distribution does not seem to be affected by the next-to-leading corrections or by the nuclear shadowing effect. In Fig. 1b) we show our results for two different choices of scale, illustrating the uncertainty due to this particular choice. We find that, in the central rapidity region, the number of charm quark pairs produced per unit rapidity in central Au-Au collisions at RHIC is 0.6 for the scale $Q = 2m_c$ and 0.9 for the scale $Q = m_c$.

In hadronic collisions, one usually defines the “K-factor” as a measure of

the size of higher-order corrections. Here we define the *effective* K-factor for *nuclear* collisions as a ratio of the particular distribution to the leading-order distribution without any nuclear effects. In Fig. 2 we present our results for the K-factor. We show that in hadronic collisions K-factor is about 2 (squares), while the *nuclear* K-factor is about 1.4 (circles) in the central rapidity region ($|y| \leq 3$). This is due to the fact that the nuclear shadowing effect effectively suppresses production of charm quarks by about 30%.

In Fig. 3 we present our results for the transverse momentum distribution of the charm quark produced in Au-Au collisions at RHIC (solid line). We find that both higher-order correlations and the nuclear effects change the shape of p_T distribution. The nuclear shadowing effect is much stronger at low p_T (about 40% effect), while at $p_T = 6\text{GeV}$ it reduces the cross section by only few percent. The next-to-leading order corrections give a factor of 1.7 increase at low p_T and about factor of 3 at $p_T = 6\text{GeV}$. These two effects together result in effective K-factor increasing from 1 at $p_T = 1\text{GeV}$ to 3 at $p_T = 6\text{GeV}$. At large p_T , where nuclear shadowing effects are negligible, we expect K-factor to approach its hadronic value. We find similar behavior of the K-factor for x_F distribution, namely its strong dependence on x_F [15].

By integrating differential distributions over the phase space we obtain the total number of charm quark pairs produced. For central (inelastic) Au-Au collisions we get about 4 (1) charm quark pairs produced per event.

To obtain the effective A-dependence of the total inclusive charm cross section in nuclear collisions, defined as $\sigma_{tot}^{charm} = A^\beta \sigma_c^{pp}$, we use the total charm cross section in hadronic collisions at $\sqrt{s} = 200\text{GeV}$, $\sigma_c^{pp} = 0.18\text{mb}$. We find that $\beta = 1.27$ for central collisions and $\beta = 1.94$ for inelastic collisions.

To be able to determine the fraction of central or inelastic events which contain at least one charm quark pair, we need to consider the semiclassical probability of having at least one parton-parton collision at fixed impact parameter, $1 - e^{-T_{AA}(b)\sigma_c}$, where $e^{-T_{AA}(b)\sigma_c}$ is the probability that there is *no* parton-parton scattering in Au-Au collision at impact parameter b . The fraction of events in Au-Au collisions that contain at least one charm quark pair is then given by

$$\frac{\sigma_c^{AA}}{\sigma_{inelastic}^{AA}} = \frac{\int d^2b [1 - \exp(-T_{AA}(b)\sigma_c)]}{\int d^2b [1 - \exp(-T_{AA}(b)\sigma_{in}^{pp})]} \quad (10)$$

where T_{AA} is given by Eq. (5) and σ_c is the integrated charm cross section ¹

$$\sigma_c = \int_{\frac{4m_c^2}{s}}^1 dx_a \int_{\frac{4m_c^2}{x_a s}}^1 dx_b \sum_{i,j}^{partons} [F_{i/A}(x_a, Q^2) F_{j/A}(x_b, Q^2) \hat{\sigma}_{i,j}(\hat{s}, m_c^2, Q^2)] \quad (11)$$

The parton cross section $\hat{\sigma}_{i,j}(\hat{s}, m_c^2, Q^2)$ has been calculated to the order $O(\alpha_s^3)$ and can be written as [17]

$$\hat{\sigma}_{i,j}(\hat{s}, m_c^2, Q^2) = \frac{\alpha_s^2(Q^2)}{m_c^2} f_{i,j}(\rho, \frac{Q^2}{m_c^2}), \quad (12)$$

where

$$f_{i,j}(\rho, Q^2/m_c^2) = f_{i,j}^{(0)}(\rho) + 4\pi\alpha_s(Q^2)[f_{i,j}^{(1)}(\rho) + \bar{f}_{i,j}^{(1)}(\rho) \ln(Q^2/m_c^2)]. \quad (13)$$

The functions $f_{i,j}^{(0)}$, $f_{i,j}^{(1)}$, and $\bar{f}_{i,j}^{(1)}$, are given in Ref. 17.

To determine the fraction of all *central* events that contain at least one charm quark pair we integrate Eq. (9) over the small range of impact parameter, i.e. $0 \leq b \leq 0.1 fm$. We find that about 98% of central events will contain at least one charm quark pair. For *inelastic* collisions we integrate Eq. (9) over all impact parameter and find this fraction to be 38%. Note that the integrated charm cross section in Eq. (9) includes multiple independent parton-parton scatterings which means multiple charm quark pair production.

To conclude, we have presented the complete next-to-leading order calculation of the differential and total inclusive cross sections for the charm production in Au-Au collisions. We have shown that at RHIC energies, both higher-order contributions and the nuclear shadowing effect are large and can not be neglected. In the central region of the rapidity distribution, the higher-order contributions increase the cross section by a factor of 2, while the nuclear shadowing effect result in additional decrease of about 30%. These two effects together result in *nuclear* K-factor of about 1.4. On the other hand, in case of the p_T distribution, the K-factor changes from 1 at

¹ The total cross section for heavy-quark production in hadronic collisions has been previously calculated using the Eq. (11) and found to be in agreement with UA1 data on bottom production at $\sqrt{s} = 630 GeV$ [16].

$p_T = 1\text{GeV}$ to 3 at $p_T = 6\text{GeV}$. The effective A -dependence for the charm production in the central (inelastic) collisions is found to be $A^{1.27}$ ($A^{1.94}$). By properly incorporating multiple parton scatterings we have shown that about 98% (38%) of all central (inelastic) events at RHIC will contain charm quark pairs. We have found that at RHIC energies the dominant subprocess for charm production is gg fusion (about 95%). Therefore, future measurements of charm production in p-p, p-A and A-A collisions at RHIC energies, in addition to being a test of perturbative QCD, could provide valuable information about presently unknown A -dependence and x -dependence of the nuclear shadowing in the gluon density.

We would like to emphasize that our calculation of charm production includes next-to-leading order corrections and is performed in the standard parton model with the use of factorization theorems for hard scatterings in pQCD. As a consequence of the truncation of the perturbative series, our results *are* sensitive to the choice of the renormalization and factorization scale. We find this uncertainty to be about 40%, which is roughly an estimate for the size of the higher-order corrections. We evolve the factorization scale down to $Q = 2m_c$. The behavior of the structure functions at scales below $2m_c$ are not very well known [9]. Furthermore, we do not perform our calculation with renormalization scale below m_c , because the perturbative calculation becomes unreliable. The nuclear shadowing effect is incorporated in a simple way, namely by using the parametrization of the recent data on shadowing of the quark densities [6] with the assumption that the shadowing effect for gluons is the same. The shadowing of the gluon density, obtained perturbatively by solving the modified Altarelli-Parisi equation for the structure functions [13] is less than the observed effect for quarks [6]. Further theoretical work along these lines is necessary to have a better understanding of parton densities in the nucleus. Another approach would be to consider the role of quantum-mechanical interference in the heavy-ion collisions [18]. The most interesting result of this novel approach is that both the shadowing and the antishadowing effects are obtained without any modification of the structure functions. We expect future high precision measurements of deep-inelastic p-A scatterings and the Drell-Yan production to be able to test both the standard parton model picture and the quantum-mechanical interference effect providing an important information about the origin of the nuclear shadowing effect.

Finally, we make a remark on the possibility of detecting a signal for the

formation of quark-gluon plasma via enhanced charm production in heavy-ion collisions at RHIC. We have found that $0.6 - .9$ open charm quark pairs per unit rapidity (in the central region) will be produced in central Au-Au collisions via hard parton-parton scatterings. Even though our results seem to indicate that unrealistically high initial temperature of the quark-gluon plasma [4] is needed to overcome this size of the background, further theoretical and experimental work is needed in quantitative understanding of the nuclear shadowing effect, especially of the gluon density, before definite conclusion can be made.

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Figure Captions

Fig. 1. a) Rapidity distribution of inclusive charm quark production in Au-Au collisions at RHIC, calculated to next-to-leading order (LO+NLO) including nuclear shadowing (NS) (solid line), without NS (dotted line), only leading-order (LO) without NS (long-dashed line), and with NS (short-dashed line), b) The same calculation as above but for two different choices of the scale, $Q^2 = m_c^2$ (solid line) and $Q^2 = 4m_c^2$ (dotted line).

Fig. 2. The *effective* K-factor, $K \equiv (\frac{d\sigma_c}{dy})/(\frac{d\sigma_c}{dy})_{LO}$, for the distributions presented in Fig. 1. The K-factor for the next-to-leading order (LO+NLO) distribution without NS (squares), including NS (circles) and for the leading-order (LO) distribution with NS (diamonds). Note that $K \approx 2$ for hadronic collisions (squares).

Fig. 3. The same as in Fig. 1a) but for the transverse momentum distribution of inclusive charm quark production. Curves are labeled as in Fig. 1a).

Fig. 4. The *effective* K-factor for the transverse momentum distributions presented in Fig. 3. Labeling is the same as in Fig. 2.

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